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RF-MEMS Based Tunable Matching Network

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Abstract

This project investigates a tunable matching network using the double-slug tuner based on a distributed RF-MEMS transmission line (DMTL). The proposed design has a maximum voltage standing wave ratio (VSWR) of 16:1 with the number of match points ranging from 529 at 5 GHz to 1597 at 20 GHz. Simulation results are performed to demonstrate the capabilities of this design.

1 Introduction

Real-time adaptable RF front-ends are becoming an attractive method for dealing with the numerous communication architectures and frequency bands in use today. An important component in realizing such adaptable system is a tunable matching network that is able to maintain low loss and high linearity. Such a device could be used for tuning microwave amplifiers to operate in various modes or in different frequency bands. RF-MEMS have the capability of implementing these tunable matching networks with minimal degradation to the overall amplifier performance.

Recently, several researchers have applied RF-MEMS to the development of tunable matching networks. Papapolymerou et al.[1] have developed a double stub tunable matching network that can real impedances between 1.5 Ω and 109 Ω and imaginary impedances between -j107 Ω and j48 Ω at 20 GHz; and real loads between 3 Ω and 94 Ω and imaginary impedances between -260 Ω and 91 Ω at 10 GHz to a 50 Ω system impedance. Jung et al.[2] developed an analog tunable matching network. A resonant cell is used with the RF-MEMS switch providing a shunt capacitance to ground, increasing the impedance tuning range. This design has been demonstrated to match impedances in the second and third quadrants of the Smith Chart while operating from 23.5 to 25 GHz. This paper presents the implementation of a double-slug tuner [3] using a distributed MEMS transmission line (DMTL) [4].

2 Double-slug tuner structure

The basic idea of an analog double-slug tuner is shown in Fig. 1. The two 90° sections determine the center frequency

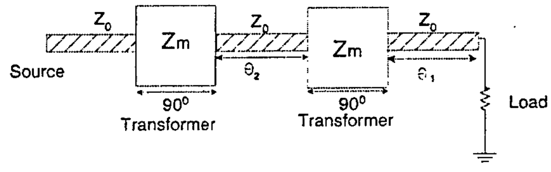


Figure 1: Schematic of a double-slug tuner.

and the lengths θ_1 and θ_2 define the impedance point being matched. The tuner operates by sliding the two slugs along the transmission line to match the load impedance to the source. A maximum VSWR is achieved when the two slugs are separated by 90° (θ_2=90°). This maximum VSWR is determined by the impedance of the 90° sections and is given by:

$$VSWR_{max} = \left(\frac{Z_0}{Z_m}\right)^4 \tag{1}$$

For example, with Z_m=25 Ω and Z_0=50 Ω, the maximum VSWR is 16:1. By decreasing the value of Z_m, the VSWR value will be increased; however as this impedance is decreased, the insertion loss of the tuner will increase.

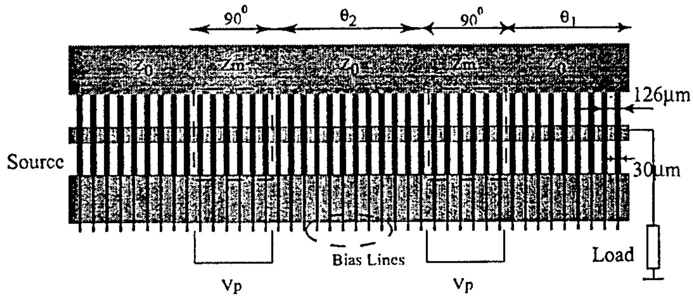


Figure 2: The topology of a double-slug tuner implemented with a DMTL.

On the basis of this double-slug tuner, a distributed MEMS transmission line is used to implement a tunable matching network as shown in Fig. 2. The DMTL is designed on a high-impedance CPW line and each RF-MEMS switch has an individual bias line. With the switch in the up-state, the CPW line is capacitively loaded down to 50 Ω. When the switch is actuated, the capacitive load increases such that the transmission line impedance is lowered to be the desired value (eg. 25 Ω). This matching network can be adjusted for different load impedances by varying the spacing between the slugs and for different center frequencies by varying the physical length of the 90° slugs.

3 Design and Simulation Results

The DMTL double-slug tuner is designed on a quartz substrate (ε_r=3.78) using a finite ground CPW line [5] with G/W/G=100μm/100μm/100μm, where G and W are respectively the gap and width of the center conductor of the CPW line. The unloaded CPW line has an impedance of 96 Ω (Z_{ul}).

3.1 Design equations

For the 90° sections, the phase change is defined as [6]:

$$\beta = n_{90} * \omega\sqrt{sL_t(sC_t + C_b)} \tag{2}$$

where n_{90} is the number of switches for the 90° section, ω is the frequency, and C_b is the switch down-state capacitance. L_t and C_t are the unloaded transmission line inductance and capacitance per unit length, and s is the switch spacing. By choosing the desired slug impedance, Z_m, the required down-state bridge capacitance is found to be:

$$C_b = \frac{sL_t}{{Z_m}^2} - sC_t \tag{3}$$

where

$$C_t = \frac{\sqrt{\varepsilon_{eff}}}{Z_{ul}} \tag{4}$$

The spacing is determined by choosing the desired number of switches needed for the 90° slug (n_{90}) at the operating frequency:

$$s = \frac{1}{n_{90}}[\frac{1}{4}(\frac{\lambda_0}{\sqrt{\varepsilon_{eff}}}\frac{Z_m}{Z_{ul}})], \tag{5}$$

where $[\frac{1}{4}(\frac{\lambda_0}{\sqrt{\varepsilon_{eff}}}\frac{Z_m}{Z_{ul}})]$ represents the quarter wavelength of the 90° section. The total number of the RF-MEMS beams is calculated as:

$$N = n_{90}(3\frac{Z_0}{Z_m} + 2) \tag{6}$$

where Z_0 is the impedance for the up-state of the switch and Z_m is the down-state impedance. Therefore the total length of the DMTL will be:

$$l = s \cdot N \tag{7}$$

The capacitance ratio is calculated as:

$$C_r = (\frac{Z_0}{Z_m})^2 \frac{(Z_{ul})^2 - (Z_m)^2}{(Z_{ul})^2 - (Z_0)^2} \tag{8}$$

and for Z_{ul}=96 Ω, Z_0=50 Ω, and Z_m=25 Ω, the capacitance ratio is found to be 5.1.

3.2 RF-MEMS Contactless Switch

Capacitive RF-MEMS switches, as used in this research, typically have a capacitance ratio of at least 20 and as high as 100 when the beam is pulled down onto the dielectric [7]. Although such a high capacitance ratio is necessary for RF switches, it becomes a problem when the RF-MEMS devices are used as loading capacitors in a distributed MEMS transmission line where the capacitance ratio must be limited to 2-5. Additionally, the intimate contact that occurs between the RF-MEMS beam and the dielectric leads to problems with switch reliability [8]. One method that has been used by several researchers to control the capacitance ratio is to place a metal-air-metal capacitor in series with the RF-MEMS capacitor [9][10]. Although this allows very accurate up- and down-state impedances to be realized, it does not address the reliability problems due to contact with the dielectric.

In an attempt to address both the capacitance ratio and switch reliability, we have developed a contactless RF-MEMS switch as shown in Fig. 3.

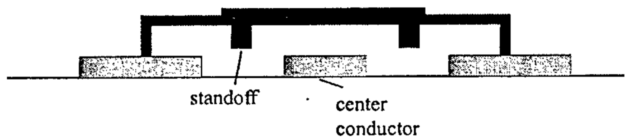


Figure 3: The contactless RF-MEMS switch.

By fabricating standoffs on the bottom side of the RF-MEMS beam its range of motion is limited. Therefore, by properly designing the standoff height and location, the capacitance ratio can be controlled and the beam is prevented from contacting the center conductor. As seen in Fig. 3 and Fig. 4 , the center part of the beam is much thicker than

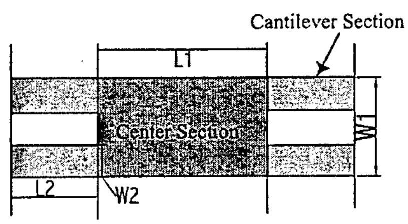


Figure 4: The top view of one bridge section.

the cantilever section. This design is used to prevent the center part of the beam from bending when the switch is actuated. The spring constant for this switch design is modelled as four cantilevers with guided ends and is 5.2 N/m for the design parameters given in Table 1 where $_1$, $_2$ are the thickness of the beam for the center part and the

Table 1: design parameters.

n_{90}	8	W_1	30 μm
C_{b0}	28 fF	L_1	128 μm
C_b	93 fF	t_1	3.5 μm
s	126 μm	W_2	10 μm
C_r	5.1	L_2	80 μm
h_{up}	2 μm	t_2	0.6 μm
h_{down}	0.4 μm		

cantilever part (see Fig. 4).

3.3 CPW ground plane design

The RF-MEMS switches of the proposed tunable matching network are connected with individual bias lines. In order to control the movement of each bridge independently, the bias lines should be isolated. MIM (metal insulator metal) capacitors are implemented in the CPW ground plane to separate the DC bias lines while maintaining the RF ground plane.

3.4 Simulation Results

To demonstrate the matching performance and frequency tunability, a calculation is carried out with 64 switches spaced 158 μm apart (total length is 1 cm). Z_m is arbitrarily decided to be 25 Ω, and 8 switches are chosen for the 90° section at 10 GHz. Using *tl* [11] to simulate the DMTL for every possible position of the two 'slugs', the match points are determined with transmission line loss of 0.6 dB/cm and switch loss of 0.1 Ω included. For 10 GHz operation, there are 1177 possible matched points, shown in Fig. 6(a) and the Smith Chart is well covered with match points. To increase the center frequency of the tuner to 20 GHz, the number of switches in the 90° section is reduced to 4, which increases the possible match points to 1597 as shown in Fig. 6(b). When the center frequency is decreased below 10 GHz, the resolution in θ_1 and θ_2 increases, but the possible number of match points is dramatically decreased due to the decreased available number of bridges for θ_1 and θ_2(seen in Fig. 6(c)). However, if we increase the length of the matching network without changing the switch spacing, we can effectively increase the operating bandwidth of the matching network.

In order to demonstrate the operation of the tuner over frequency, an impedance of 10+j50 Ω is matched at different frequencies and the frequency response is calculated in [12]. Seen from Fig. 5, as frequency changes, the bandwidth is larger, but the fractional bandwidths are relatively constant.

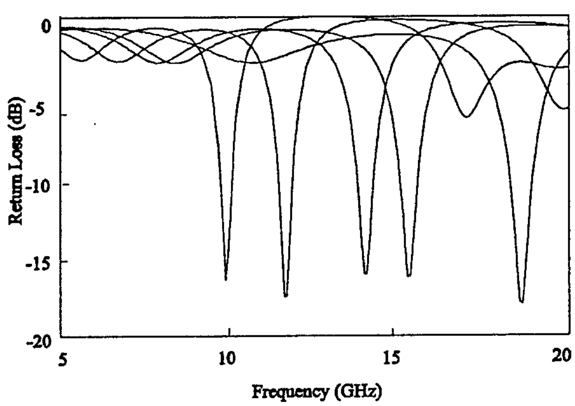
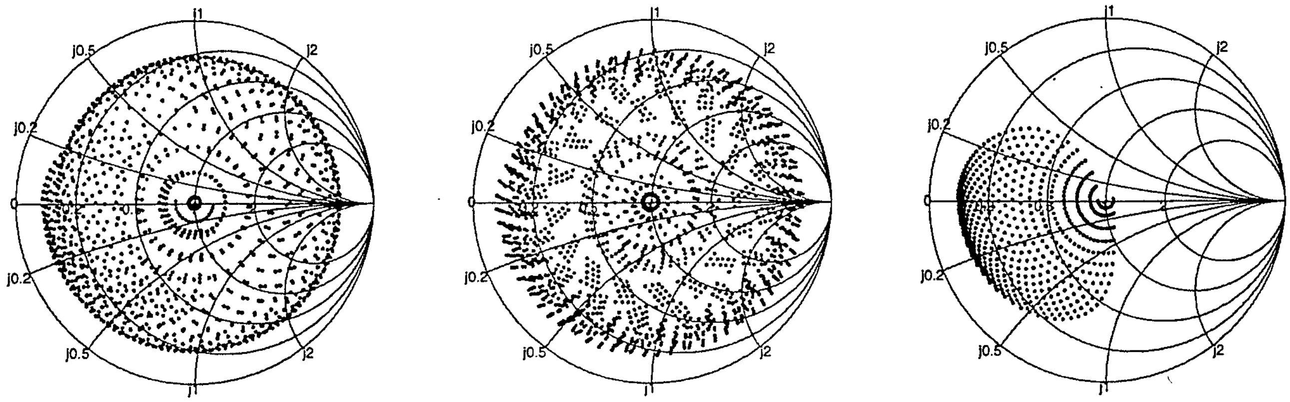


Figure 5: The frequency response of the DMTL based double-slug tuner for a load impedance of 10+j50 Ω matched at various frequencies.

4 Fabrication Procedures

The DMTL RF-MEMS tuner is fabricated on a 500 μm thick quartz wafer. First the SiCr bias lines are sputtered and defined using BOE wet etch. The SiCr thickness is 1300 Å and results in a line resistivity of 1000 Ω/sq. The center conductor and the ground planes are then defined by a lift-off process of evaporated Ti/Au/Ti=200/8000/200 Å. Then Si_3N_4 is then deposited by reactive sputtering [13]and defined with Reactive Ion Etching (RIE), which will form the insulator layer for the MIM capacitors of the ground plane. The sacrificial layer is PMMA [14] and the height of the bridges is 2 μm. The membrane layer is then deposited by sputtering a seed layer followed by plating the center part of the beams, the ground plane and part of the center conductor. Finally the bridge is defined and the sacrificial layer is removed by acetone. The bridges are released using a critical point dryer system. A photomicrograph is shown in Fig. 7.



(a) (b) (c)

Figure 6: Simulation of DMTL double-slug tuner at (a)10GHz:8 switches for the 90° and 1177 matched points (b)20GHz:4 switches for the 90° section and 1597 matched points (c)5GHz:16 switches for 90° section and 529 matched points.

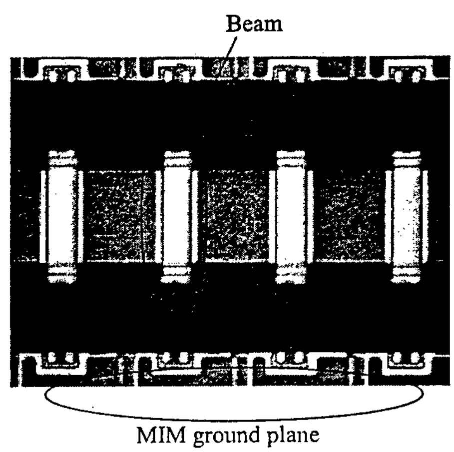


Figure 7: The photomicrograph of the fabricated device.

5 Conclusion and Discussion

In this project, an RF-MEMS based double-slug tuner is investigated. Simulations have been performed showing a very good tuning operation with good coverage of the Smith Chart. The proposed design has a maximum voltage standing wave ratio (VSWR) of 16:1 with the number of match points ranging from 529 at 5 GHz to 1597 at 20 GHz.

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